Short communication

Agreement between spatiotemporal parameters from a photoelectric system with different filter settings and high-speed video analysis during running on a treadmill at comfortable velocity

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ABSTRACT

The aim of this study was to determine the level of agreement between spatiotemporal gait characteristics from a photoelectric system with different filter settings and high-speed video analysis during running on a treadmill at comfortable velocity. Forty-nine runners performed a running protocol on a treadmill at comfortable velocity. Two systems were used to determine spatiotemporal parameters (i.e. contact time [CT], flight time [FT], step frequency [SF] and step length [SL]) during running: OptoGait system and high-speed video analysis at 1000 Hz. The collected data was re-filtered in the OptoGait software by using nine different settings (i.e. 0_0, 1_1, 2_2, 3_3, 3_4, 4_4, 4_5, 5_4 and 5_5), and compared to those obtained through video analysis. The Pearson correlation analysis revealed very large correlations ($r > 0.9$, $p < 0.001$) in CT, FT, SF and SL between both systems, regardless of the OptoGait's filter settings. The ICC reported an almost perfect association (ICC > 0.9) for both SL and SF regardless of the filter setting. However, large variations between filter settings according to the data from video analysis were reported in CT and FT (0_0, 1_1 and 2_2 filter settings obtained an association ICC > 0.9, whereas other filters obtained lower ICCs). Bland-Altman plots revealed small bias and error and no presence of heteroscedasticity of error for 1_1 setting. In conclusion, the filter setting for the OptoGait system should be considered to minimize the bias and error of spatiotemporal parameters measurement. For running on a treadmill, the 1_1 filter setting is recommended if gait parameters are to be compared to a high-speed video analysis (1000 Hz).

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1. Introduction

In recent years, a gait analysis system has gained popularity among sport scientists and clinicians (i.e. OptoGait system). It is based on the communication between two photoelectric cell bars. Interruptions in the communication between the bars occur by the participant's feet. This allows identification of gait events (initial contact and toe off). An important consideration is that the bars are configured with the LEDs 3 mm from the ground, which results in the LEDs being interrupted a few milliseconds before contact with the ground and a few milliseconds after foot off. This has an effect on the calculation of the spatiotemporal gait parameters (i.e., longer stance phase and shorter swing phase when compared to other gait analysis systems (Lee et al., 2014a,b; Lienhard et al., 2013), but its impact on the final value can be smoothed with the use of filters settings.

Filter settings (GaitR IN and OUT filter) within the OptoGait software allow the user to set the minimum number of LEDs to be interrupted for triggering the contact event. By changing this filter it is possible to reduce or eliminate discrepancies between the OptoGait system and other gait analysis systems. That was the finding of a previous work (Healy et al., 2019) that examined a range of four filter settings (i.e., 0_0, 1_1, 2_2 and 3_3) for the OptoGait system to determine the setting which most closely matched the measurements provided by a three-dimensional (3-D) motion analysis system. However, the conditions under which

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that study was conducted (e.g., walking over ground at self-selected speed) leave some questions unanswered. What about stronger filters (e.g., 3_4, 4_4, 4_5, 5_4, 5_5), other conditions (e.g., running on a treadmill) or different reference systems (e.g., high-speed video or 3-D analysis)? To date, no research has examined the effect of different filter settings on the calculated spatiotemporal gait parameters during running on a treadmill. Likewise, despite 3-D motion capture system is widely considered as the 'gold-standard' for measuring running kinematics, the high-speed video analysis has been shown to be a reliable and valid method for that purpose (Balsalobre-Fernández et al., 2017; Dingenen et al., 2018; Esculier et al., 2018; Pipkin et al., 2016) and it is clearly more affordable for clinicians and coaches so it might be of practical interest to determine comparability with this system.

Since many previous studies have used this system to measure spatiotemporal gait characteristics during running on a treadmill and the filter setting was not specified (García-Pinillos et al., 2018; Roche-Seruendo et al., 2017), it is important to determine which filter setting minimizes the bias according other systems and to establish if any specific setting would allow the results from different systems to be used interchangeably. Therefore, the aim of this study was to determine the level of agreement between spatiotemporal gait characteristics from a photoelectric system (i.e. OptoGait system) with different filter settings (i.e. 0_0, 1_1, 2_2, 3_3, 3_4, 4_4, 4_5, 5_4 and 5_5) and high-speed video analysis (1000 Hz) during running on a treadmill at comfortable velocity.

2. Methods

2.1. Participants

Forty-nine (44 men and 5 women) amateur endurance runners (age: 26 ± 8 years; height: 1.74 ± 0.07 m; body mass: 71 ± 10 kg) participated in this study, and met the inclusion criteria: (1) older than 18 years old, (2) able to run 10-km in <50 min, (3) not suffering from any injury in the last 6 months before the data collection. After receiving detailed information on the objectives and procedures of the study, participants signed an informed consent form, which complied with the ethical standards of the World Medical Association's Declaration of Helsinki (2013). The study was approved by the Institutional Review Board.

2.2. Procedures

Participants performed a running protocol on a motorized treadmill (WOODWAY Pro XL, Woodway, Inc., Waukesha, WI, USA). The initial speed was set at 8 km h^{-1}, and speed increased by 1 km h^{-1} every minute until participants felt comfortable. Then, running velocity was fixed (i.e. self-selected comfortable running velocity: 11.7 ± 1.3 km h^{-1}). The use of a self-selected velocity is common in running biomechanics studies (Queen et al., 2006; Willy et al., 2016) in order to avoid the potential influence of individual responses to an imposed running pace. Since previous studies (Lavcanska et al., 2005; Schieb, 1986) on human locomotion have shown that accommodation to running on a treadmill occurs in ~6–8 min, an 8 min accommodation program was performed at that velocity. Immediately after the accommodation interval, the recording period started. It lasted 3 min and it was performed at the same velocity. The slope was maintained at 0% over the entire protocol.

2.3. Materials and testing

Spatiotemporal parameters during running were measured: (i) contact time (CT, in seconds), (ii) flight time (FT, in seconds), (iii)

step length (SL, in meters), (iv) step frequency (SF, in steps/min). Two different systems were used to measure those parameters (OptoGait system vs. high-speed video analysis [1000 Hz]). Both systems have the same temporal accuracy (± 1 ms). For the analysis of temporal parameters (CT and FT) the right leg was selected in

Table 1
Pairwise comparisons (*t*-test) between spatiotemporal parameters (i.e. CT, FT, SL and SF) obtained from OptoGait system set with nine different filters (0_0, 1_1, 2_2, 3_3, 3_4, 4_4, 4_5, 5_4, 5_5) according to those measured through high-speed video analysis.

Variable		Mean (SD)	P-value[*]	Cohen's d[*]
CT (s)	Video analysis	0.268 (0.028)	–	–
	0_0	0.270 (0.031)	0.020	0.071
	1_1	0.263 (0.028)	<0.001	0.179
	2_2	0.253 (0.027)	<0.001	0.535
	3_3	0.243 (0.024)	<0.001	0.959
	3_4	0.237 (0.023)	<0.001	1.209
	4_4	0.235 (0.023)	<0.001	1.287
	4_5	0.228 (0.022)	<0.001	1.588
	5_4	0.232 (0.022)	<0.001	1.429
	5_5	0.226 (0.022)	<0.001	1.668
FT (s)	Video analysis	0.092 (0.026)	–	–
	0_0	0.087 (0.027)	<0.001	0.189
	1_1	0.094 (0.025)	0.003	0.078
	2_2	0.104 (0.023)	<0.001	0.488
	3_3	0.114 (0.021)	<0.001	0.930
	3_4	0.120 (0.021)	<0.001	1.184
	4_4	0.122 (0.020)	<0.001	1.293
	4_5	0.129 (0.020)	<0.001	1.595
	5_4	0.125 (0.020)	<0.001	1.422
	5_5	0.131 (0.019)	<0.001	1.712
SL (cm)	Video analysis	116.82 (12.65)	–	–
	0_0	116.06 (12.20)	0.003	0.061
	1_1	116.05 (12.20)	0.003	0.062
	2_2	116.06 (12.20)	0.003	0.061
	3_3	116.06 (12.21)	0.003	0.060
	3_4	116.06 (12.21)	0.003	0.060
	4_4	116.06 (12.21)	0.003	0.060
	4_5	116.06 (12.21)	0.003	0.060
	5_4	116.06 (12.20)	0.004	0.061
	5_5	116.06 (12.20)	0.004	0.060
SF (spm)	Video analysis	166.95 (7.36)	–	–
	0_0	168.65 (7.63)	<0.001	0.226
	1_1	168.65 (7.61)	<0.001	0.227
	2_2	168.55 (7.53)	<0.001	0.215
	3_3	168.54 (7.53)	<0.001	0.214
	3_4	168.55 (7.52)	<0.001	0.215
	4_4	168.54 (7.52)	<0.001	0.214
	4_5	168.54 (7.52)	<0.001	0.214
	5_4	168.54 (7.53)	<0.001	0.213
	5_5	168.55 (7.53)	<0.001	0.215

[*] Pairwise comparisons according to data from video analysis. CT: contact time; FT: flight time; SL: step length; SF: step frequency.

Table 2
Pearson correlation analysis between spatiotemporal parameters obtained from OptoGait system (OG) with 9 different filter settings and video analysis (VA).

	CT	FT	SL	SF
VA vs. OG0_0	0.985[***]	0.989[***]	0.991[***]	0.965[***]
VA vs. OG1_1	0.980[***]	0.985[***]	0.991[***]	0.965[***]
VA vs. OG2_2	0.971[***]	0.972[***]	0.991[***]	0.977[***]
VA vs. OG3_3	0.965[***]	0.966[***]	0.991[***]	0.977[***]
VA vs. OG3_4	0.958[***]	0.958[***]	0.991[***]	0.977[***]
VA vs. OG4_4	0.955[***]	0.954[***]	0.991[***]	0.977[***]
VA vs. OG4_5	0.953[***]	0.948[***]	0.991[***]	0.977[***]
VA vs. OG5_4	0.951[***]	0.949[***]	0.991[***]	0.977[***]
VA vs. OG5_5	0.950[***]	0.944[***]	0.991[***]	0.977[***]

[***] Indicates statistical significance for the correlation analysis (p < 0.001).

Table 3
Intraclass correlation coefficients (ICC) and confidence intervals (CI) between spatiotemporal parameters obtained from OptoGait system (OG) with different filter settings and video analysis (VA).

|	ICC (95% CI)			
	CT	FT	SL	SF
VA vs. OG0_0	0.990 (0.981–0.995)	0.984 (0.717–0.996)	0.994 (0.988–0.997)	0.969 (0.845–0.989)
VA vs. OG1_1	0.981 (0.862–0.994)	0.991 (0.980–0.995)	0.994 (0.988–0.997)	0.970 (0.844–0.989)
VA vs. OG2_2	0.914 (−0.087–0.980)	0.929 (−0.035–0.983)	0.994 (0.988–0.997)	0.977 (0.824–0.992)
VA vs. OG3_3	0.800 (−0.088–0.952)	0.808 (−0.100–0.953)	0.994 (0.988–0.997)	0.977 (0.823–0.993)
VA vs. OG3_4	0.705 (−0.071–0.923)	0.702 (−0.080–0.921)	0.994 (0.988–0.997)	0.977 (0.818–0.992)
VA vs. OG4_4	0.673 (−0.072–0.912)	0.668 (−0.080–0.909)	0.994 (0.988–0.997)	0.977 (0.824–0.993)
VA vs. OG4_5	0.588 (−0.057–0.879)	0.576 (−0.063–0.873)	0.994 (0.988–0.997)	0.977 (0.822–0.993)
VA vs. OG5_4	0.636 (−0.071–0.897)	0.627 (−0.079–0.893)	0.994 (0.988–0.997)	0.977 (0.818–0.993)
VA vs. OG5_5	0.557 (−0.057–0.865)	0.542 (−0.062–0.857)	0.994 (0.988–0.997)	0.977 (0.818–0.993)
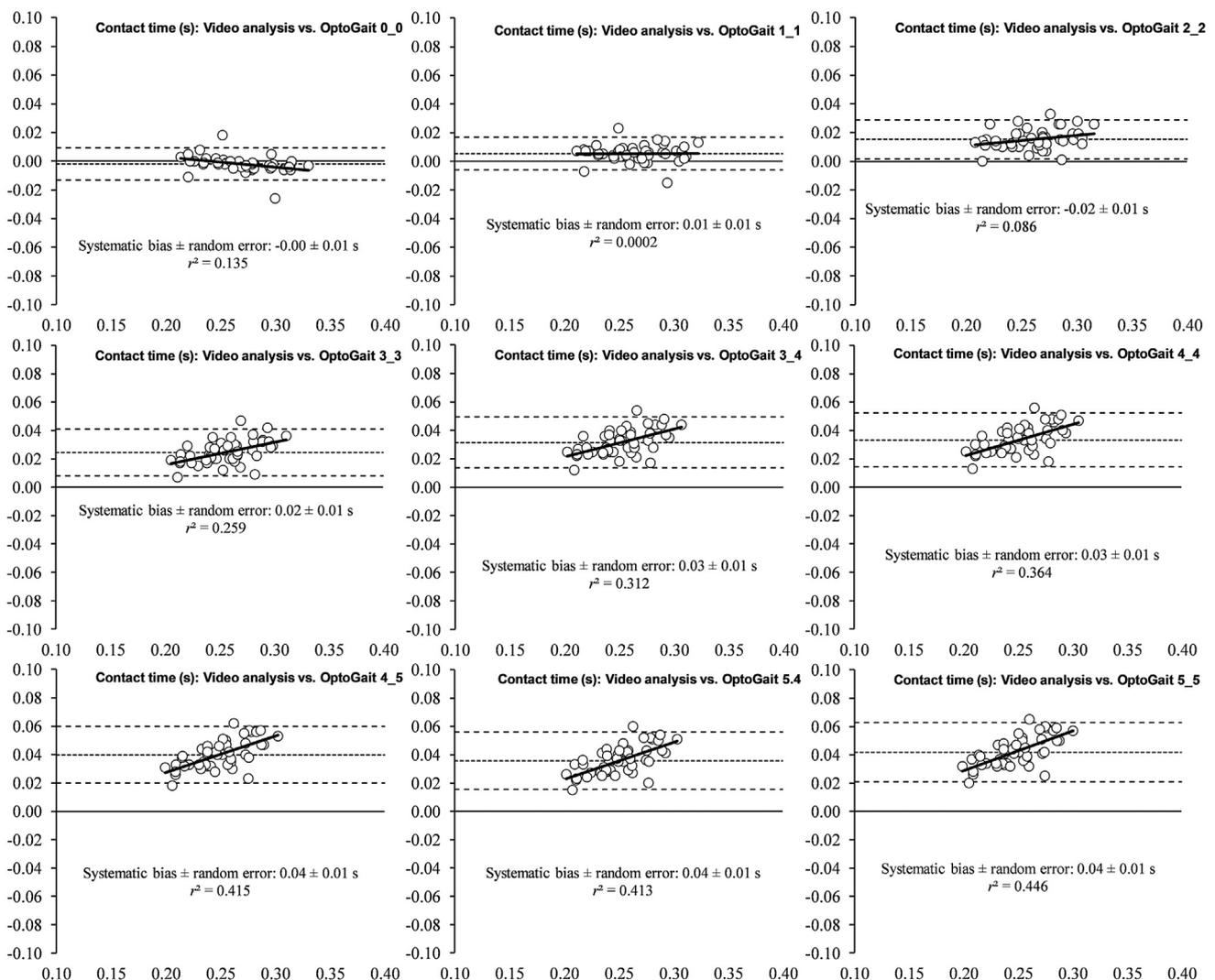
Fig. 1. Bland-Altman plots for the measurement of contact time (CT) during running at self-selected comfortable speed for both systems (OptoGait with different filter settings vs. high-speed video analysis). The plot includes the mean difference (dotted line) and 95% limits of agreement (dashed lined), along with the regression line (solid line).

order to control potential confounding factors (i.e., asymmetry (Radzak et al., 2017)). Further information about the systems:

- The OptoGait system (Optogait; Microgate, Bolzano, Italy): Previous papers have analysed the validity and reliability of this system during walking (Gomez Bernal et al., 2016; Healy et al., 2019; Lee et al., 2014a,b; Lienhard et al., 2013). The two parallel bars of the device system were placed on the side edges of the treadmill at the same level as the contact surface. Spatiotemporal parameters were measured for every step during the 30-s recording interval (between 1:30 and 2:00 min of the recording period of each participant). Within the OptoGait system the default setting for the identification of gait events is 0_0 (i.e., CT begins when at least 1 LED is activated and finished once the number of LEDs activated returned to 0). After data collection, data was re-filtered in the OptoGait software (Gait IN and OUT filter) with eight more filter settings (i.e., 1_1, 2_2, 3_3, 3_4, 4_4, 4_5, 5_4 and 5_5). Together with the default setting (i.e., 0_0), a total of 9 filter settings were considered in the current work.
- High-speed video analysis: Two-dimensional video data were simultaneously collected at 1000 Hz using a high-speed camera (Imaging Source DFK 33UX174, The Imaging Source Europe GmbH; Germany). Range of interest (ROI) was adjusted to achieve 1000 fps (784 × 144 resolution). Some previous papers

have concluded that high-speed video analysis is a valid (Balsalobre-Fernández et al., 2017; Esculier et al., 2018) and reliable (Dingenen et al., 2018; Pipkin et al., 2016) system for measuring frontal and sagittal plane kinematics during running. Based on a previous work (Padulo et al., 2014), speed data from treadmill was tested and small differences, <0.05%, were obtained according to the measured speed – tests done with and without a subject running and in a wide range of speeds from 8 to 18 km h^{-1}. Accordingly, speed given by the treadmill was considered to SL calculations. The camera was placed perpendicular to the treadmill from a posterior view at 2 m from the center of the treadmill and at a height of 0.80 m. The 30 s videos were recording between 1:30 and 2:00 min of the recording period of each participant. Then, videos were analysed using the open license software Kinovea (version 0.8.27), and spatiotemporal parameters were determined. The CT and FT were measured for every step by identifying both the initial contact and the take-off frames and counting frames in-between; whereas SL and SF were calculated as follows (derived for each step):

(1) *Step time (ST, in seconds) = FT (s) + CT (s),*
(2) *SF (steps s^{-1}) = 1/ST (s)*
(3) *SF (steps min^{-1}) = 60 × SF (steps s^{-1})*
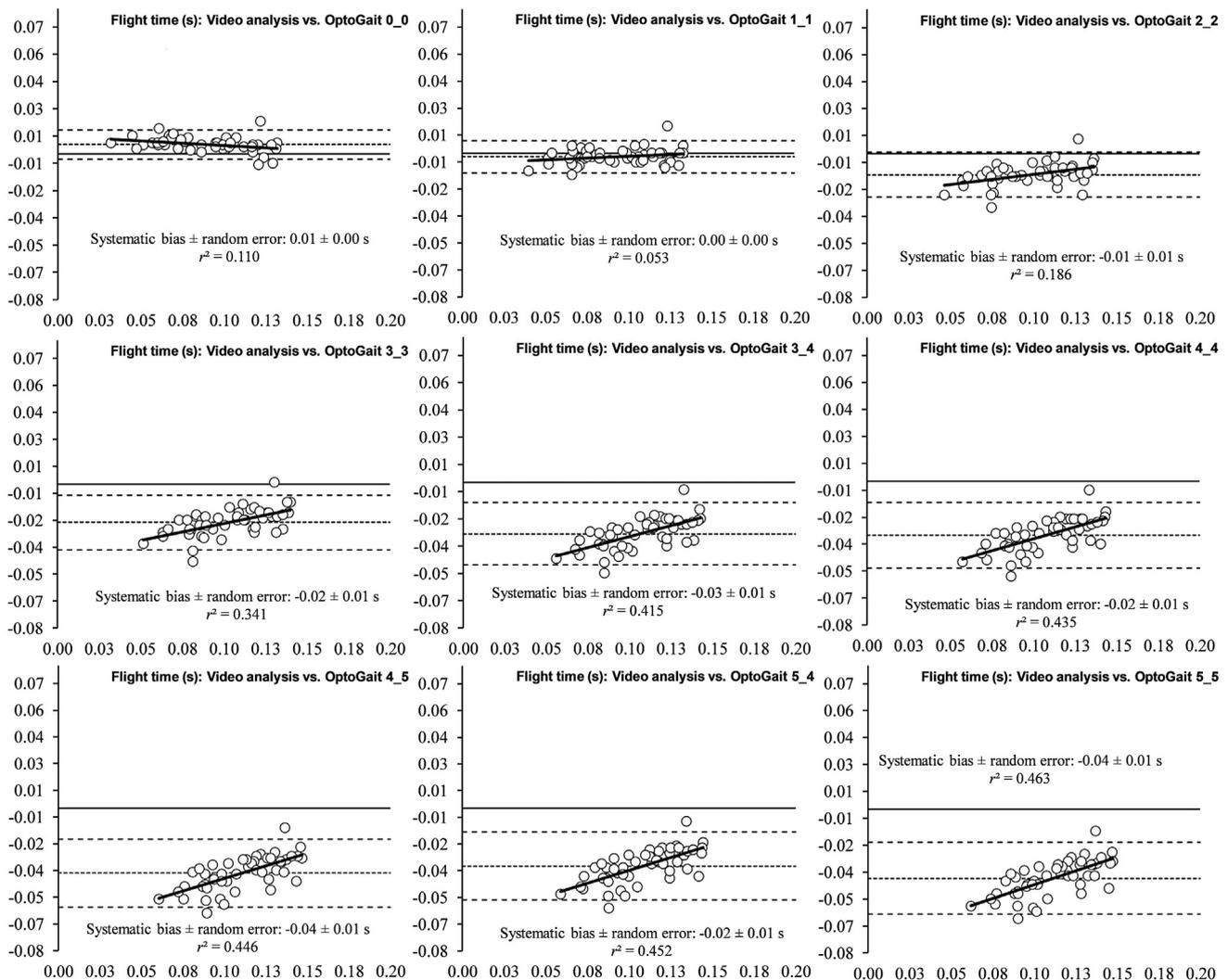(4) *SL (m) = running velocity (m s^{-1})/SF (steps s^{-1})*

Fig. 2. Bland-Altman plots for the measurement of flight time (FT) during running at self-selected comfortable speed for both systems (OptoGait with different filter settings vs. high-speed video analysis). The plot includes the mean difference (dotted line) and 95% limits of agreement (dashed lined), along with the regression line (solid line).

2.4. Statistical analysis

Descriptive statistics are represented as mean standard deviation (SD). Tests of normal distribution and homogeneity, determined by the Shapiro-Wilk and Levene's test, respectively, were conducted on all data before analysis. Mean comparisons (i.e. *t*-tests) were conducted between spatiotemporal parameters from OptoGait system with different configuration of the system's hardware, as compared to spatiotemporal parameters from high-speed video analysis. The magnitude of the differences between values was also interpreted using the Cohen's d effect size (*ES*) (between-group differences) (Cohen, 1988). To determine the level of agreement between each configuration of the OptoGait system and the video analysis, a Pearson correlation analysis was performed between spatiotemporal parameters from each filter setting of OptoGait system and video analysis (Hopkins et al., 2009). Additionally, intraclass correlation coefficients (ICC) were calculated. Based on the characteristics of this experimental design and following the guidelines reported by Koo and Li (2016), the authors decided to conduct a "two-way random-effects" model (ICC [2,k]), "mean of measurements" type, and "absolute" definition for the ICC measurement. Finally, the Bland-Altman (Bland and Altman, 1995) limits of agreement method (mean difference ± 1.96 SD) was used to examine differences between each fil-ter setting and data from video analysis for each spatiotemporal parameter (CT, FT, SL and SF). Heteroscedasticity of error was defined as an $r^2 > 0.1$ (Atkinson and Nevill, 1998). The level of significance used was p < 0.05. Data analysis was performed using the SPSS (version 22, SPSS Inc., Chicago, Ill).

3. Results

The paired *t*-test showed significant differences in the magnitude of each spatiotemporal parameter measured through the OptoGait system with different filters according to the data obtained from the high-speed video analysis (Table 1). For the CT, significant differences were found between both systems, with the OptoGait's default setting (i.e. 0_0) showing the lowest difference according to the video analysis (p = 0.020, ES = 0.071), whereas the 5_5 setting reported the highest difference (p < 0.001, ES = 1.668). For the FT, the lowest difference according to the video analysis (p = 0.003, ES = 0.078) was reported with 1_1 filter setting, whereas the 5_5 setting reported the highest difference (p < 0.001, ES = 1.712). For SL and SF, the differences according to the video analysis were similar regardless the filter setting used (SL: p = 0.003–0.004, ES = ~0.06; SF: p < 0.001, ES = ~0.22).

Very large correlations (r > 0.9, p < 0.001) were obtained in CT, FT, SF and SL between both systems, regardless of the OptoGait's
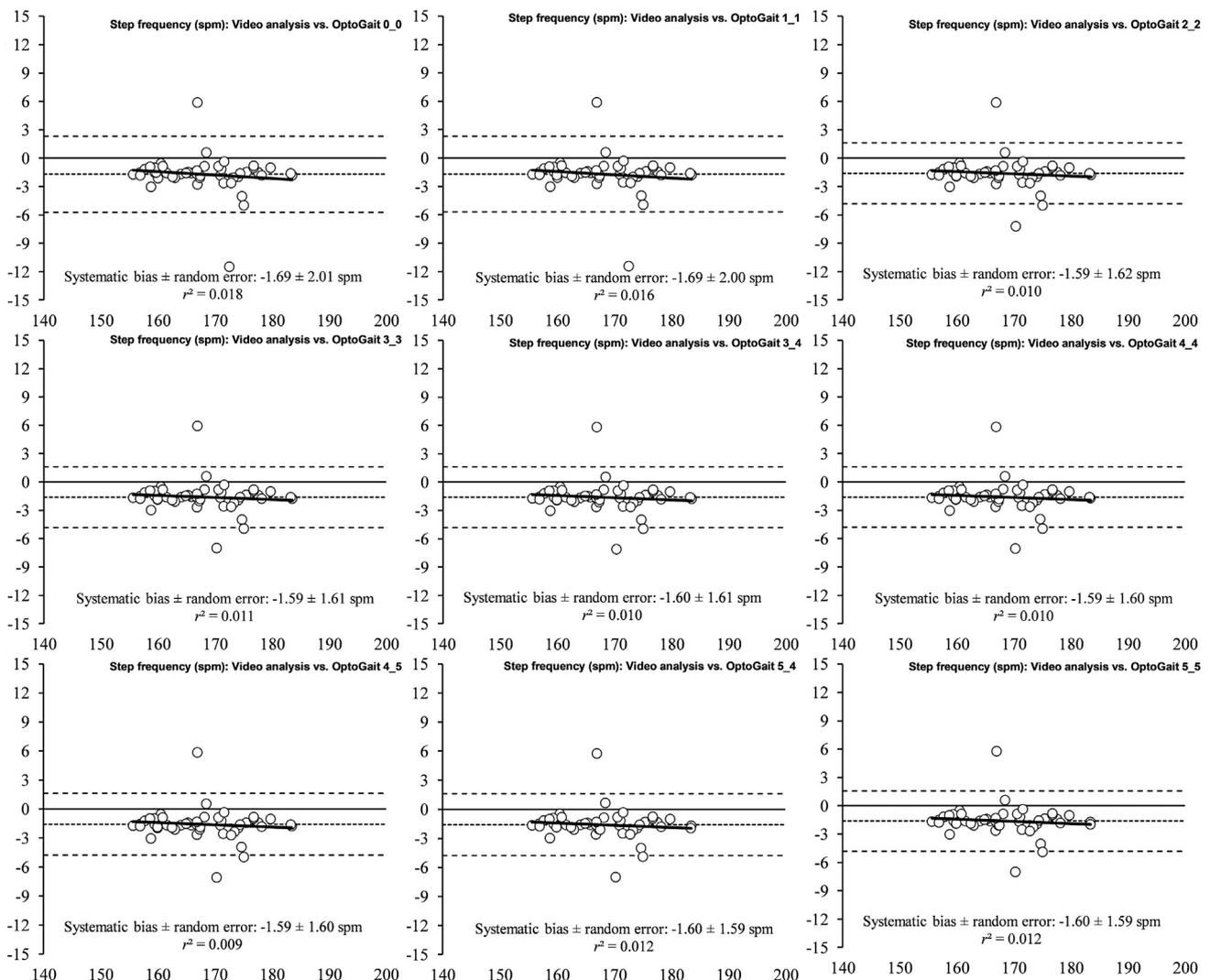

Fig. 3. Bland-Altman plots for the measurement of step length (SL) during running at self-selected comfortable speed for both systems (OptoGait with different filter settings vs. high-speed video analysis). The plot includes the mean difference (dotted line) and 95% limits of agreement (dashed lined), along with the regression line (solid line).

filter settings (Table 2). The ICC reported an almost perfect association (ICC > 0.9) for both SL and SF, regardless of the filter setting used in the OptoGait system. In contrast, for both CT and FT the ICC reported large variations between filter settings according to the data from high-speed video analysis. Whereas the 0_0, 1_1 and 2_2 filter settings obtained an almost perfect association (ICC > 0.9), the correlation was weaker with other settings (even ICC < 0.6 with 4_5 and 5_5 filter settings) (see Table 3).

For the CT (Fig. 1), Bland-Altman plots revealed heteroscedasticity of error for each filter setting apart from 1_1 and 2_2 ($r^2 < 0.1$), with higher differences for the 4_5, 5_4 and 5_5 settings (0.04 ± 0.1, $r^2 = {\sim}0.4$). For the FT (Fig. 2), all filter settings revealed heteroscedasticity of error ($r^2 > 0.1$) except for the 1_1 ($r^2 = 0.053$), with higher differences for the 4_5 and 5_5 settings (0.04 ± 0.1, $r^2 = {\sim}0.5$). For both SF and SL (Figs. 3 and 4, respectively), no heteroscedasticity of error was found ($r^2 < 0.1$) and systematic bias and error was similar regardless of the filter setting.

4. Discussion

This study highlights the influence of the filter settings on the estimation of spatiotemporal parameters from the OptoGait system. During running on a treadmill at comfortable velocity, the use of the OptoGait 1_1 filter settings induced small differences (i.e., low systematic bias and random errors, with no presence of heteroscedasticity of error) as compared to high-speed video analysis. Moreover, as the filter settings were stronger, the bias and error were greater.

Previous studies have used the OptoGait system as the criterion measure for the analysis of spatiotemporal parameters during running (Balsalobre-Fernández et al., 2017; García-Pinillos et al., 2018). However, none of the aforementioned studies considered the influence of the configuration for the OptoGait system (i.e., filter setting). Just one study (Healy et al., 2019) examined the influence of the OptoGait filter setting on the accuracy of spatiotemporal parameters assessment. This work (Healy et al., 2019) involved 18 healthy adults who walked at comfortable pace over ground, and spatiotemporal data were re-filtered through 4 different settings (0_0, 1_1, 2_2 and 3_3). The four settings demonstrated high concurrent validity with the motion capture system (according on ICCs), however, a significant systematic bias was evident between the 3-D system and the OptoGait 0_0 and 1_1 settings (OptoGait values were higher for stance phase and lower for swing phase) (Healy et al., 2019). Healy et al. (2019) recommended the use of the 2_2 filter setting within the OptoGait software if gait parameters are to be compared to a 3-D motion capture system.
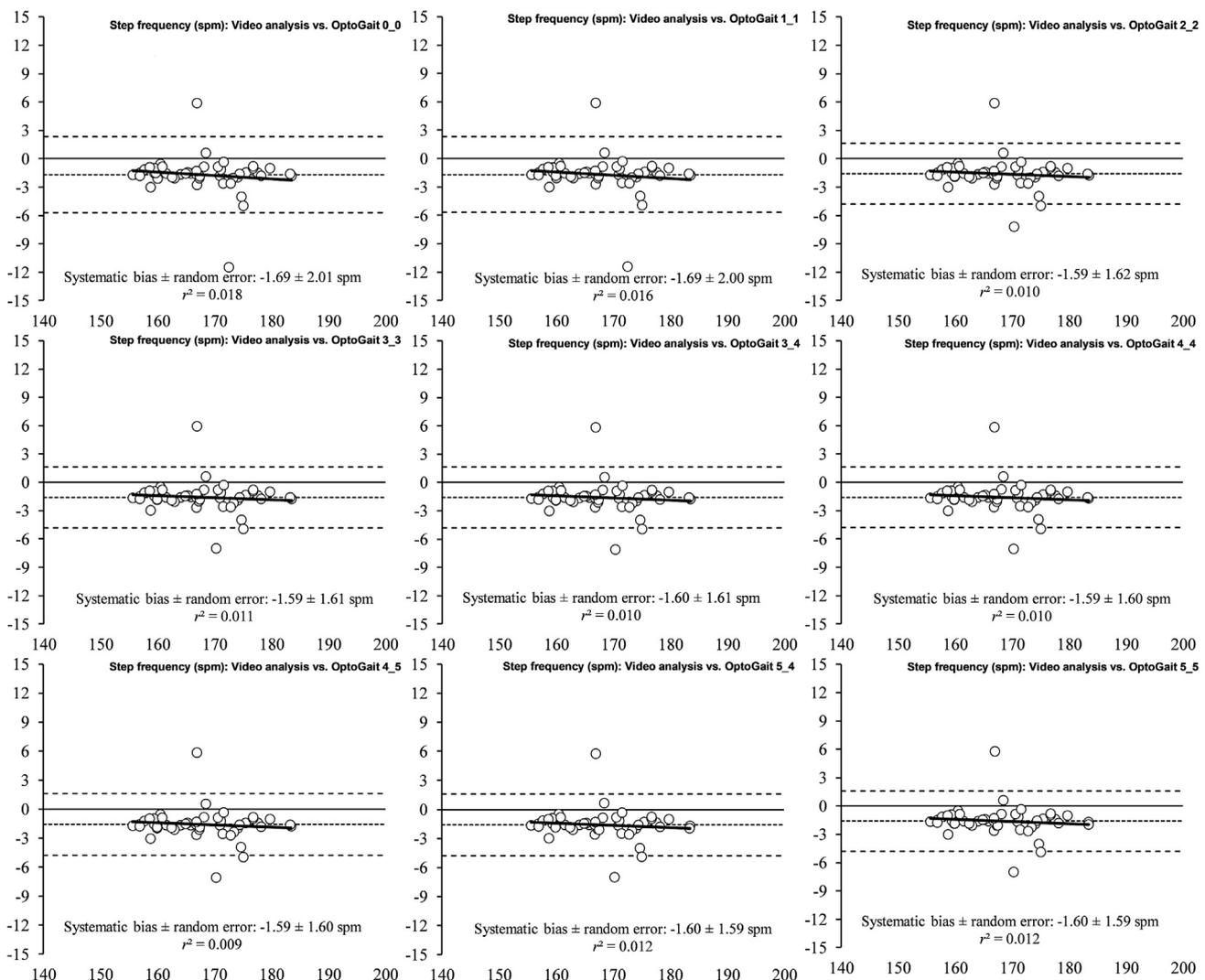

Fig. 4. Bland-Altman plots for the measurement of step frequency (SF) during running at self-selected comfortable speed for both systems (OptoGait with different filter settings vs. high-speed video analysis). The plot includes the mean difference (dotted line) and 95% limits of agreement (dashed lined), along with the regression line (solid line).

The results reported by the current study do not match with those obtained by Healy et al. (2019). Whereas the correlation analysis reported a large relationship between values obtained from different filter settings (i.e. nine settings) and video analysis, the ICCs revealed some differences between settings (0_0, 1_1 and 2_2 filter settings obtained an almost perfect association, with lower ICCs for the rest of settings), and that finding was supported by the Bland-Altman analysis which revealed that the lowest values of bias and error according to high-speed video analysis were obtained with 1_1 setting, with higher biases when filter settings were stronger. Nevertheless, some methodological contrasts between the aforementioned experiment (Healy et al., 2019) and the current research may help to explain differences between study's findings. First, the criterion measure used (i.e., high-speed video analysis vs. 3-D motion analysis). Even though the high-speed video analysis has been shown to be a reliable and valid method to measure running kinematics (Balsalobre-Fernández et al., 2017; Dingenen et al., 2018; Esculier et al., 2018; Pipkin et al., 2016), the 3-D motion capture system is widely considered as a 'gold-standard' for this purpose. Second, the protocol itself (i.e. running vs. walking), with clear kinematic differences between walking and running (Cappellini et al., 2006). Third, the surface (i.e., treadmill vs. over ground running). Despite previous papers (Riley et al., 2008; Schache et al., 2001) have concluded that treadmill-based analysis of running kinematics may be generalized to over ground conditions, the influence on SL and SF is well documented (Riley et al., 2008; Schache et al., 2001). It seems clear that those factors might influence results but, even so, findings from both works are in consonance by highlighting the importance of filter setting for the OptoGait system.

Finally, the context and conditions in which these data were collected must be considered to properly interpret these results. This protocol was performed on a treadmill, at 0% gradient and at a constant velocity (i.e. self-selected comfortable velocity). All these points create a 'controlled environment' (Riley et al., 2008) that may influence spatiotemporal gait characteristics, and it makes the authors doubt about the repeatability of these findings during running under other conditions (e.g., slopes, velocities, over ground). More research is clearly needed to analyse the accuracy of different filter setting for the OptoGait system during running under those conditions (e.g., larger ranges of slopes and velocities).

In conclusion, this study highlights the importance of filter setting for the OptoGait system in order to minimize the bias and error of spatiotemporal parameters measurement. During running on a treadmill, the 1_1 filter setting is recommended if gait parameters are to be compared to a high-speed video analysis (1000 Hz).

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Declaration of Competing Interest

The authors declare that they have no competing interests.

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